A Multi-Resolution Approach to Climate Modeling

Todd Ringler
Theoretical Division
Los Alamos National Laboratory

Bill Skamarock
National Center for Atmospheric Research

Max Gunzburber
Florida State University

LA-UR 10-02460

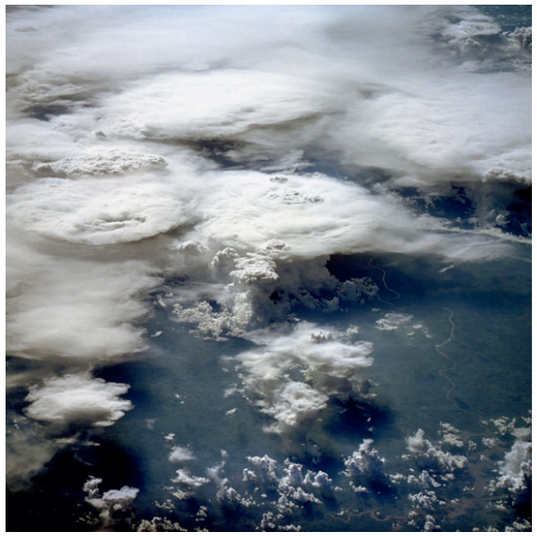
Climate, Ocean and Sea-Ice Modeling Project
http://public.lanl.gov/ringler/ringler.html

Los Alamos NATIONAL LABORATORY EST. 1943

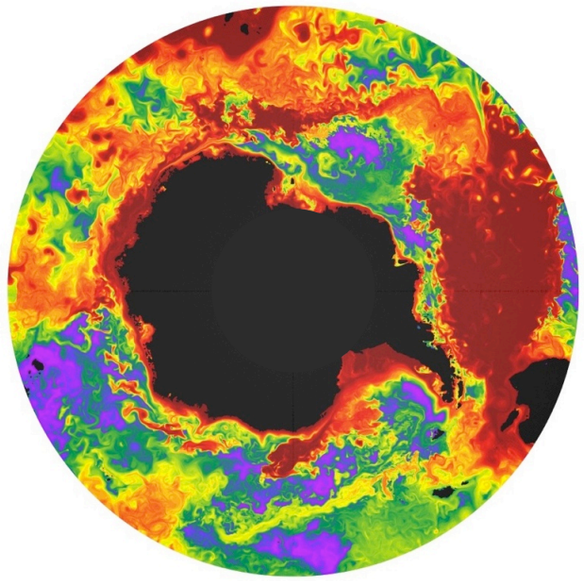
Office of Science U.S. DEPARTMENT OF ENERGY

Examples of processes that are currently unresolved.

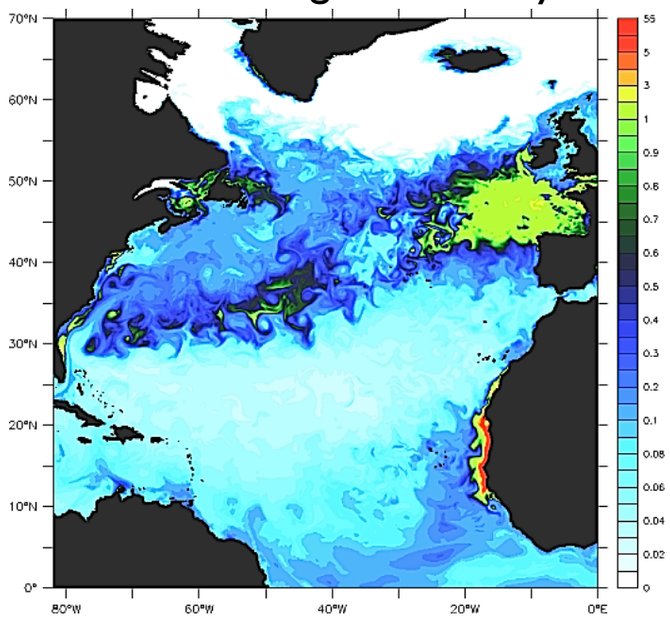
Cloud Processes



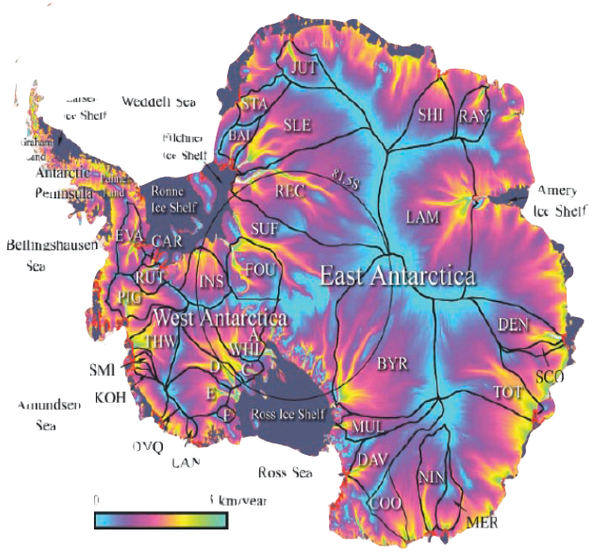
Ocean/Atmosphere Interaction



Ocean Biogeochemistry



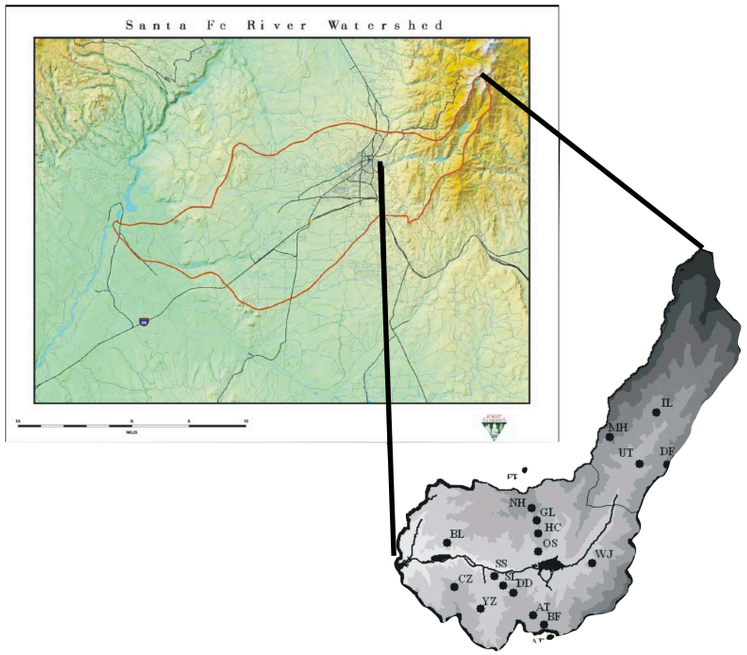
Ocean/Ice Shelf Interaction



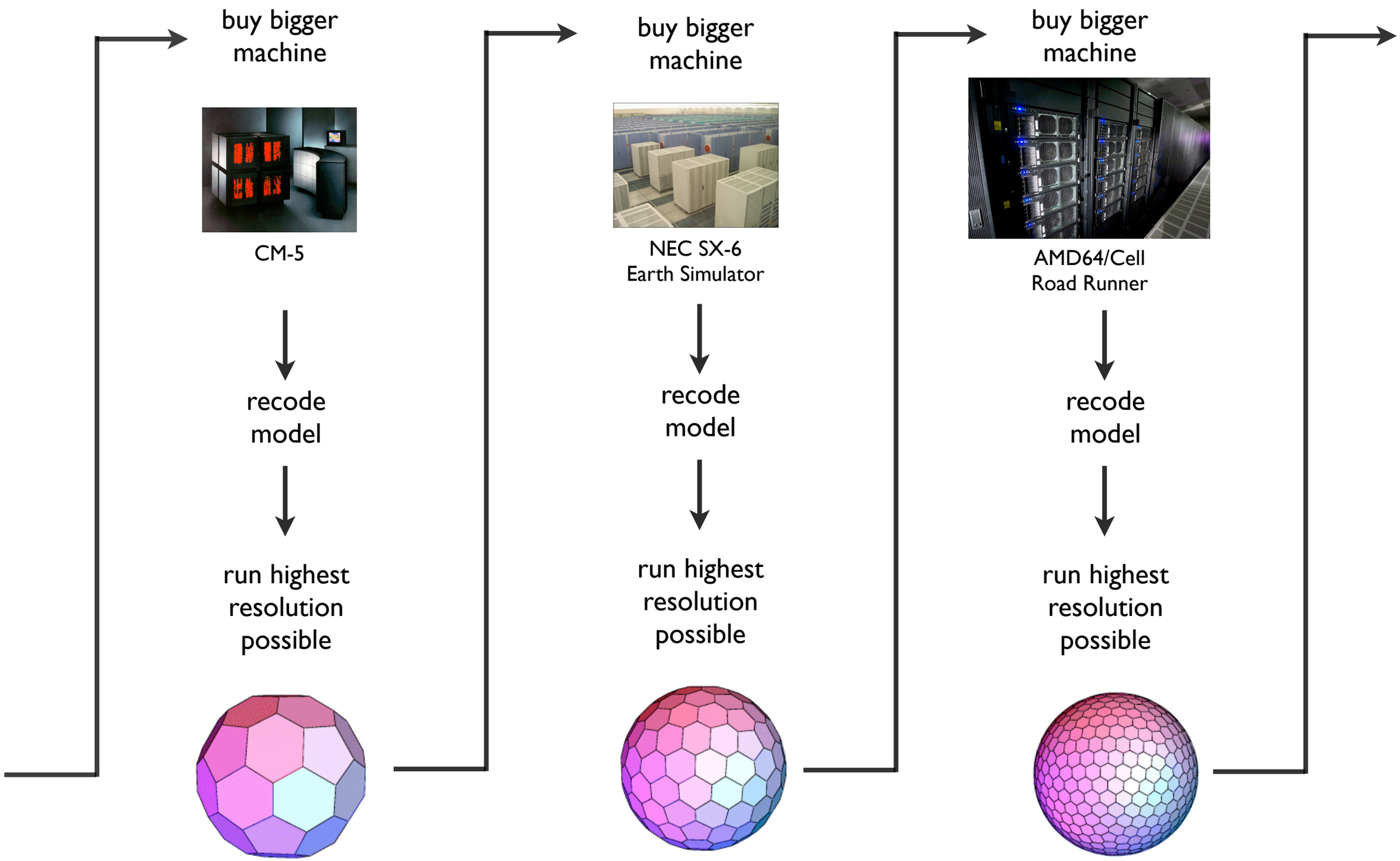
Each of these examples demonstrate scale-sensitive processes that might impact the climate system in a fundamental and important way.

The length scale of these processes is O(km).

Hydrology in Complex Terrain



Modus Operandi of Climate System Modeling



Bigger, faster computers are fantastic. Recoding for those machine is simply the cost of progress. The question is how do we distribute those resources?

How do we get there with the current paradigm?

A quick back-of-the-envelope analysis should be very concerning to mid-career scientists:

IPCC resolution ~ 100 km

Target resolution ~ 1 km

Ratio of where we are to where we want to be ~ 2^7

Increase in computational resource required ~ 8^7 ~ 2e6

Time to reach target assuming a doubling in resources every 18 months ~ **22 years**

Looking at the massive effort required to increase the resolution climate models, 22 years is not unrealistic. Maybe it is 15 years, or maybe it it 25 years. Either way, it is a long time.

The climate modeling community would benefit from an additional approach that allows some of these processes to be resolved at some locations.

We could then consider the notion of approaching the target from additional directions, for example by expanding the areas over which these fine-scale processes are simulated.

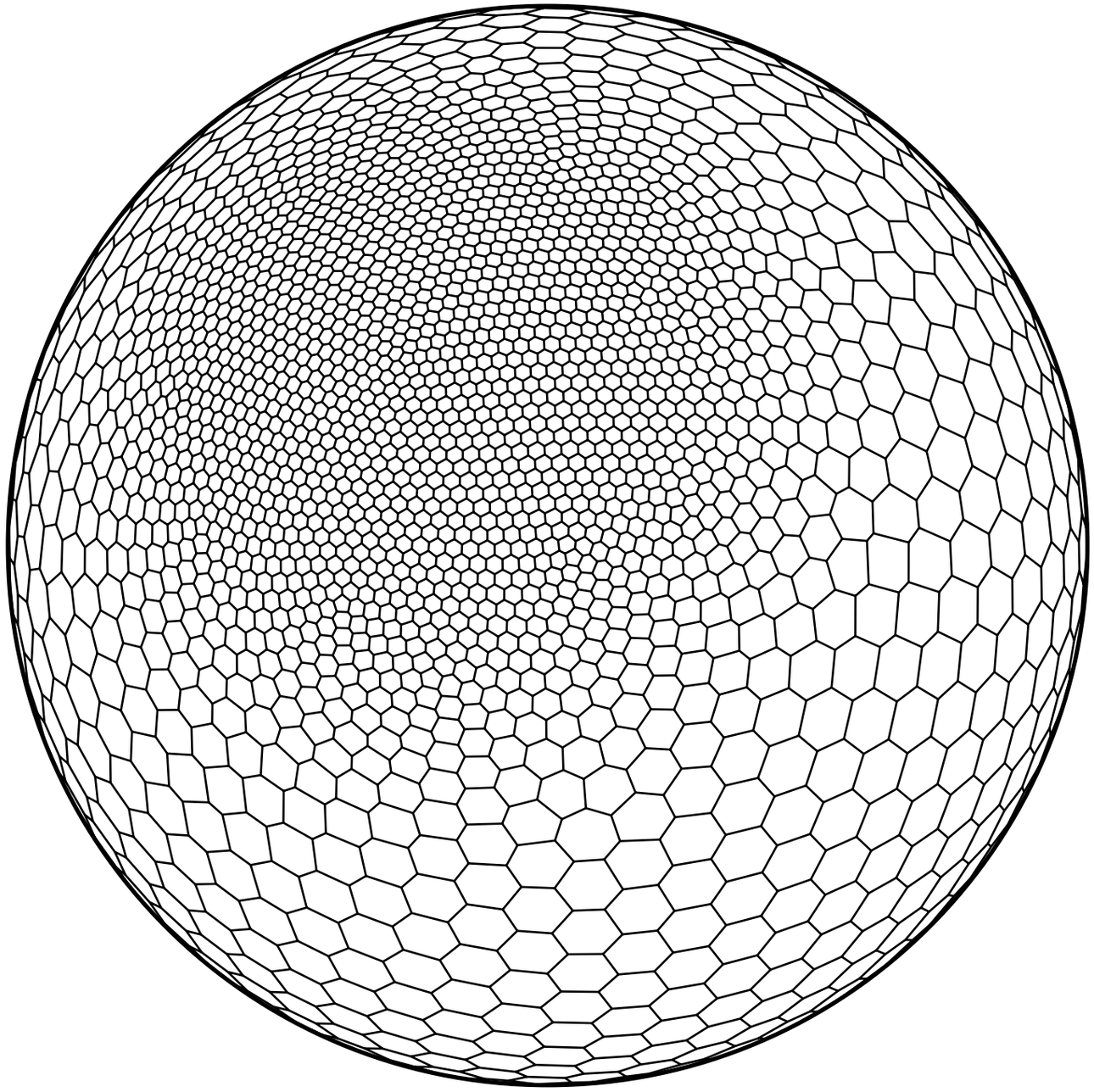
A multi-resolution approach based on Spherical Centroidal Voronoi Tessellations

Underlying principles of this approach:

1. This is a global modeling framework

2. The approach allows us to "paint" the sphere with regions enhanced resolution.

3. The resulting mesh is conforming (i.e. no hanging nodes) and is a Voronoi diagram.



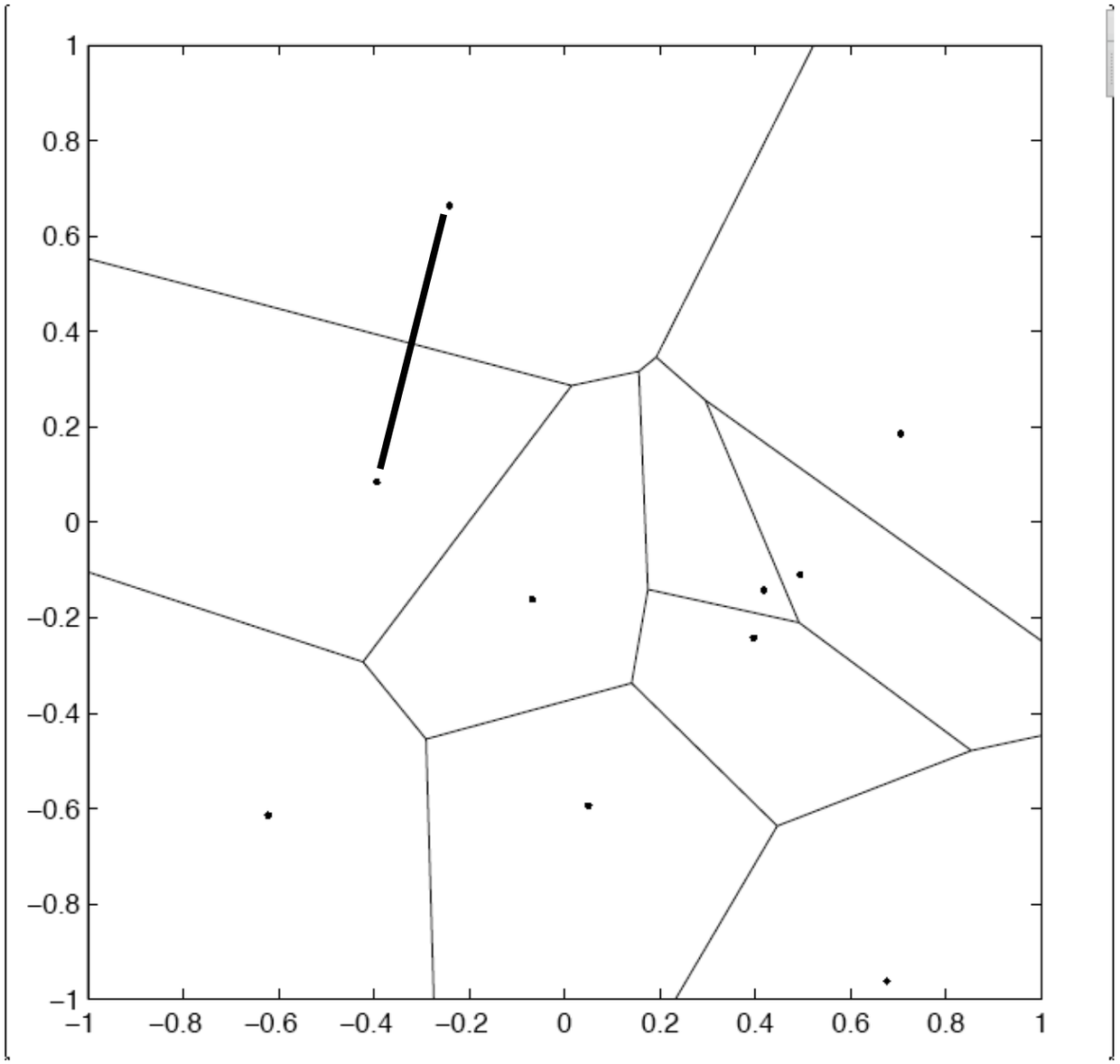
Definition of a Voronoi Tessellation

Given a region, S, and a set of generators, z_i ...

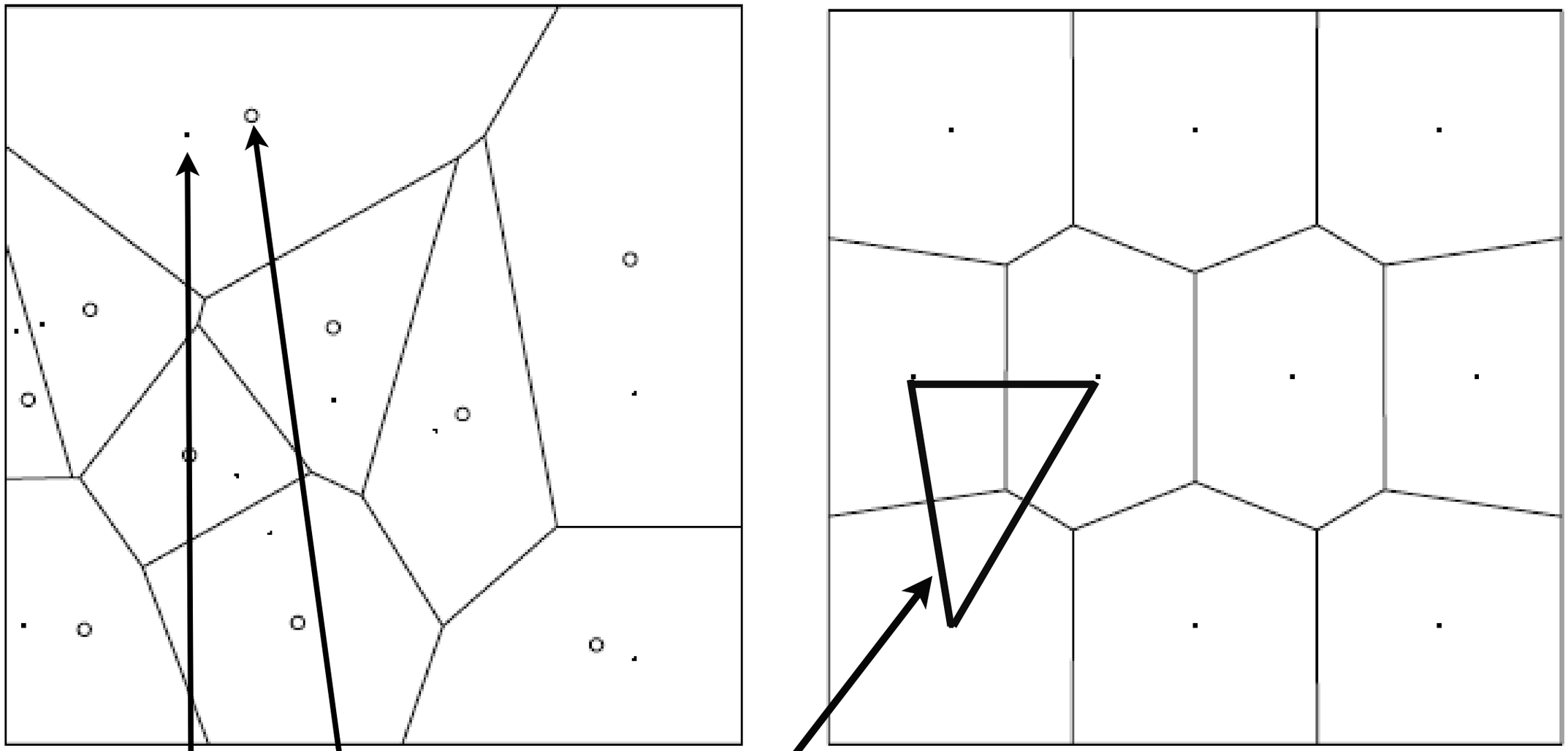
The Voronoi region, V_i, for each z_i is the set of all points closer to z_i than z_j for j not equal to i.

We are guaranteed that each edge (aka face) is shared by exactly two generators.

We are guaranteed that the line connecting generators is orthogonal to the shared edge and is bisected by that edge.



Definition of a Centroidal Voronoi Tessellation



Dual tessellation

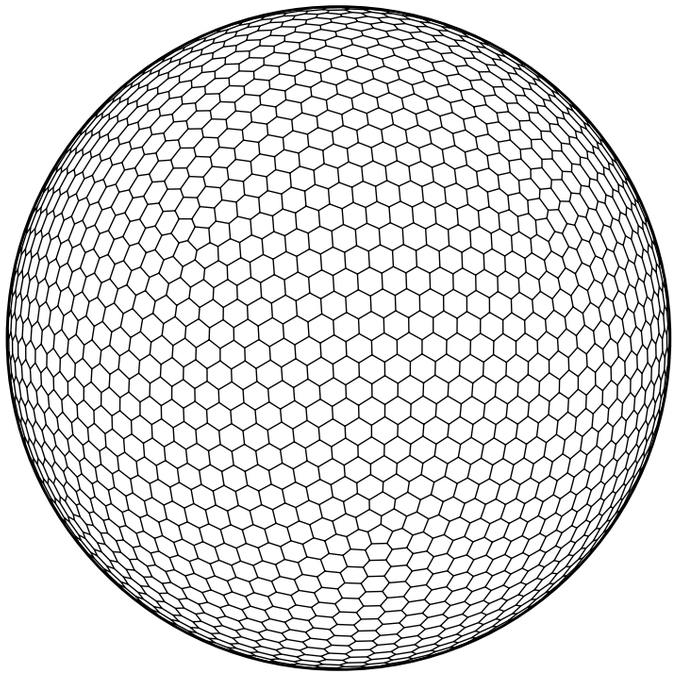
z_i

z_i^* = center of mass wrt a **user-defined** density function

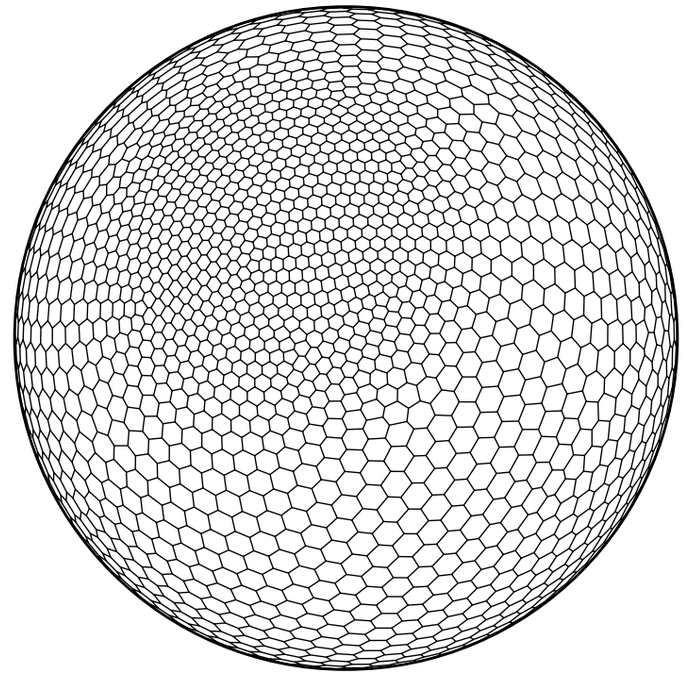
$$z^* = \frac{\int_V w\rho(w)\,dw}{\int_V \rho(w)\,dw}$$

Spherical Centroidal Voronoi Tessellations (SCVTs):

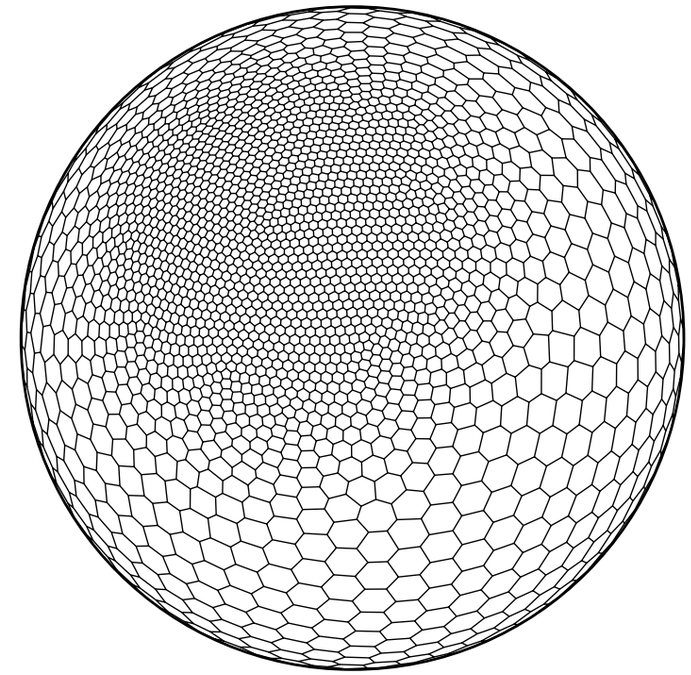
various ways to distribute 2562 nodes on the sphere.



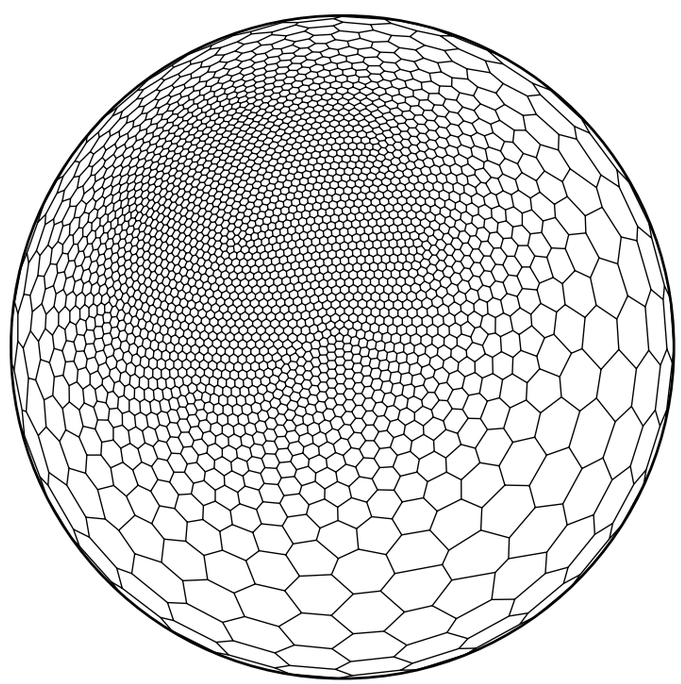
x1



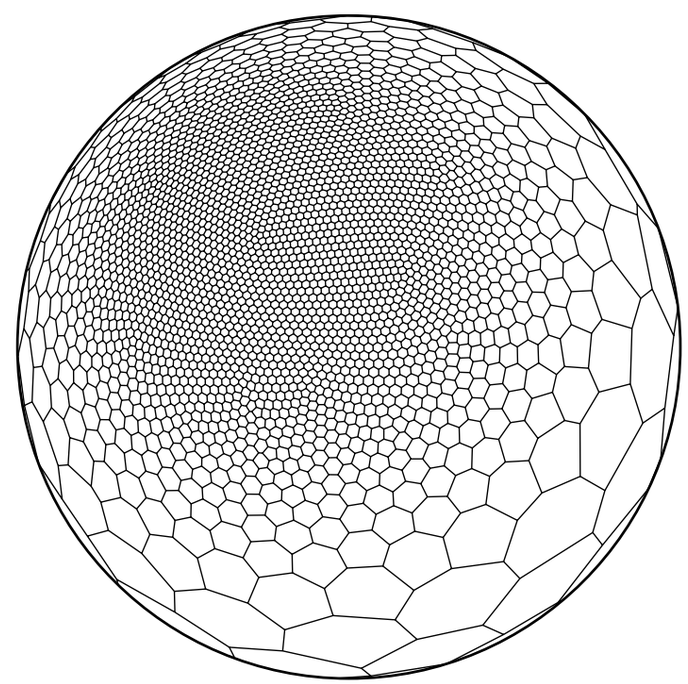
x2



x4

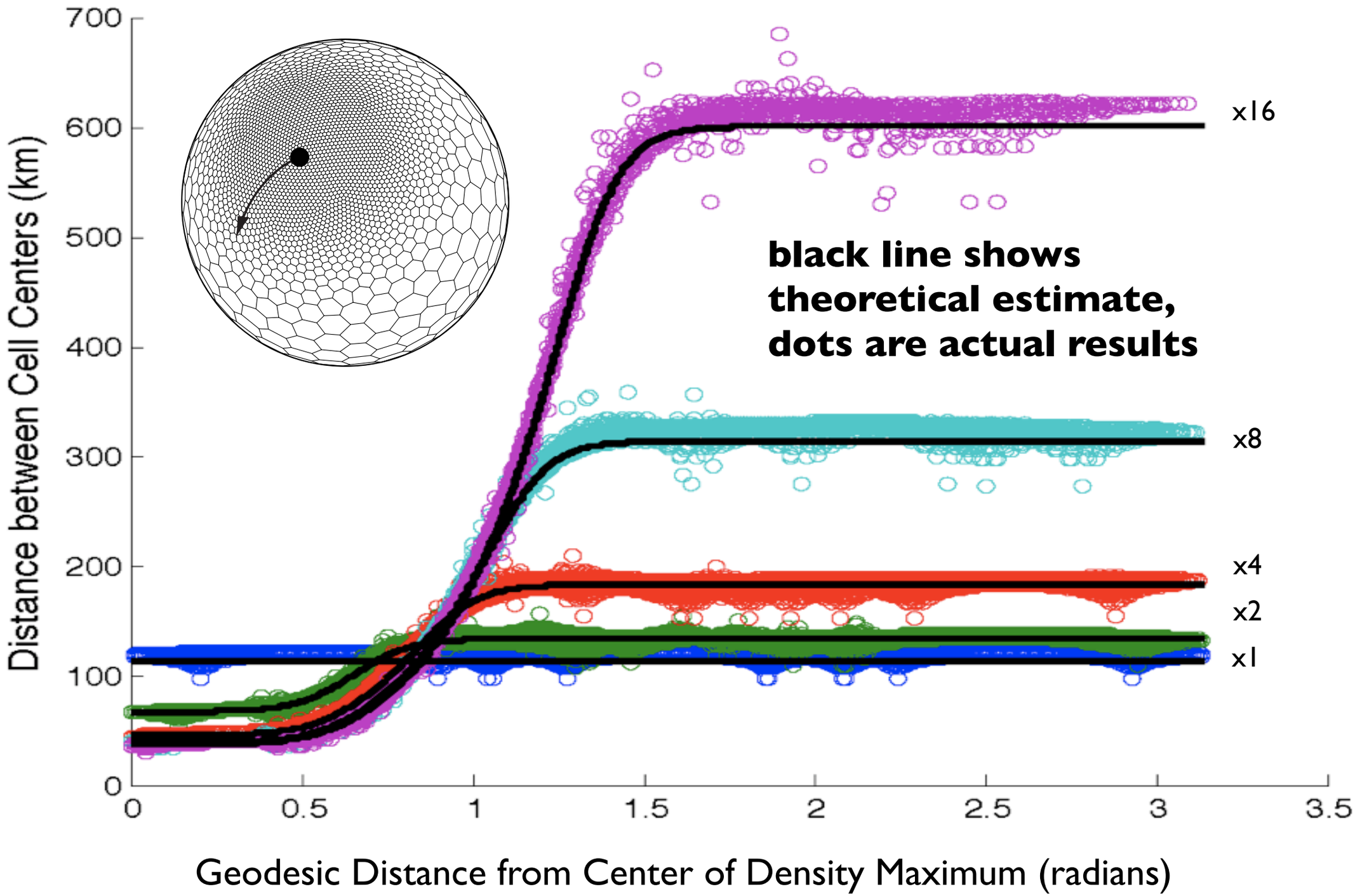


x8



x16

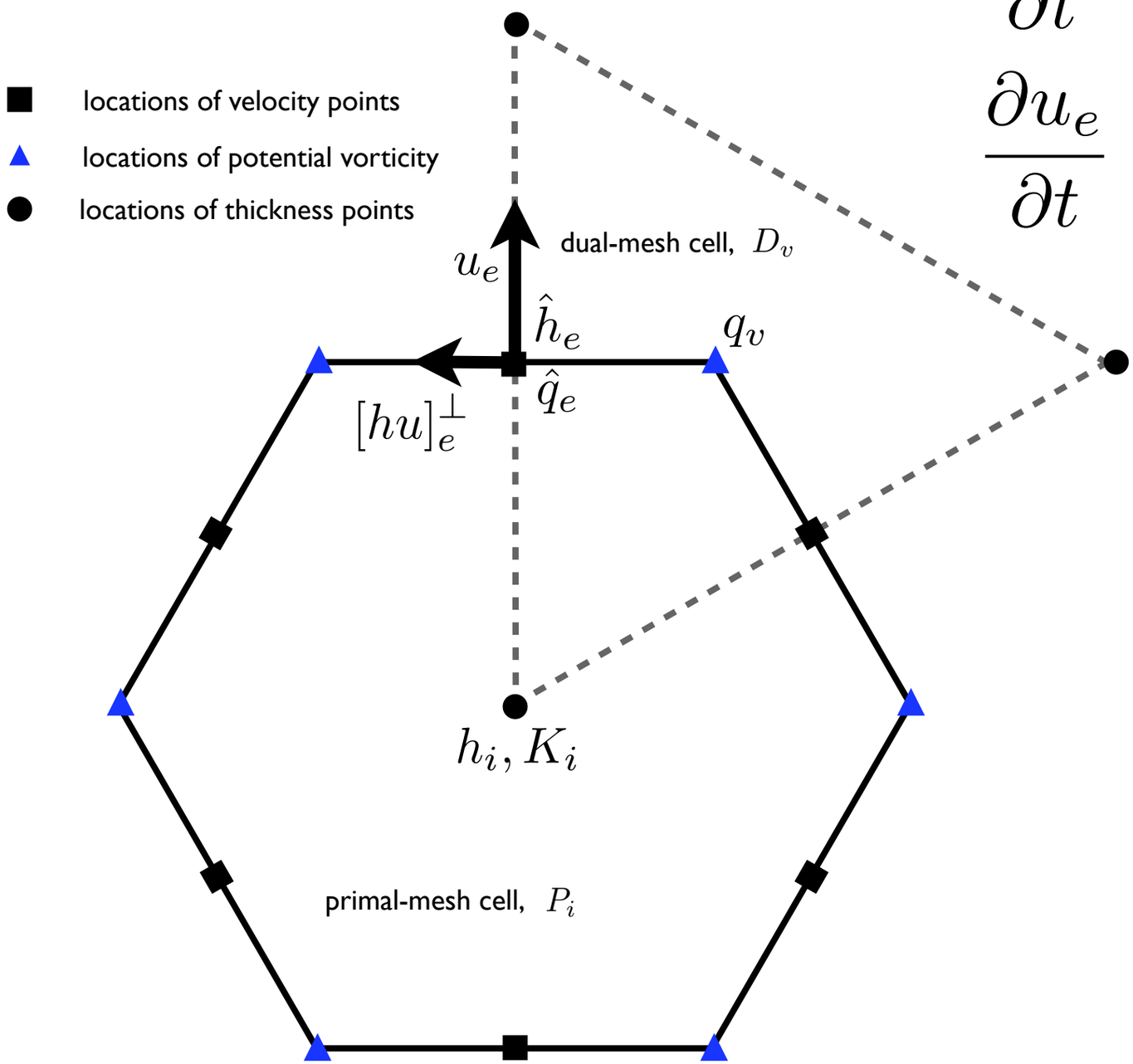
We have precise control over the distribution of cells.



Construction of a multi-resolution finite volume method

$$\frac{\partial h_i}{\partial t} + \left[\nabla \cdot \left(\widehat{h}_e u_e\right)\right]_i = 0$$

$$\frac{\partial u_e}{\partial t} + \widehat{q}_e \left[hu\right]_e^{\perp} = \left[\nabla \left(g h_i + K_i\right)\right]_e$$

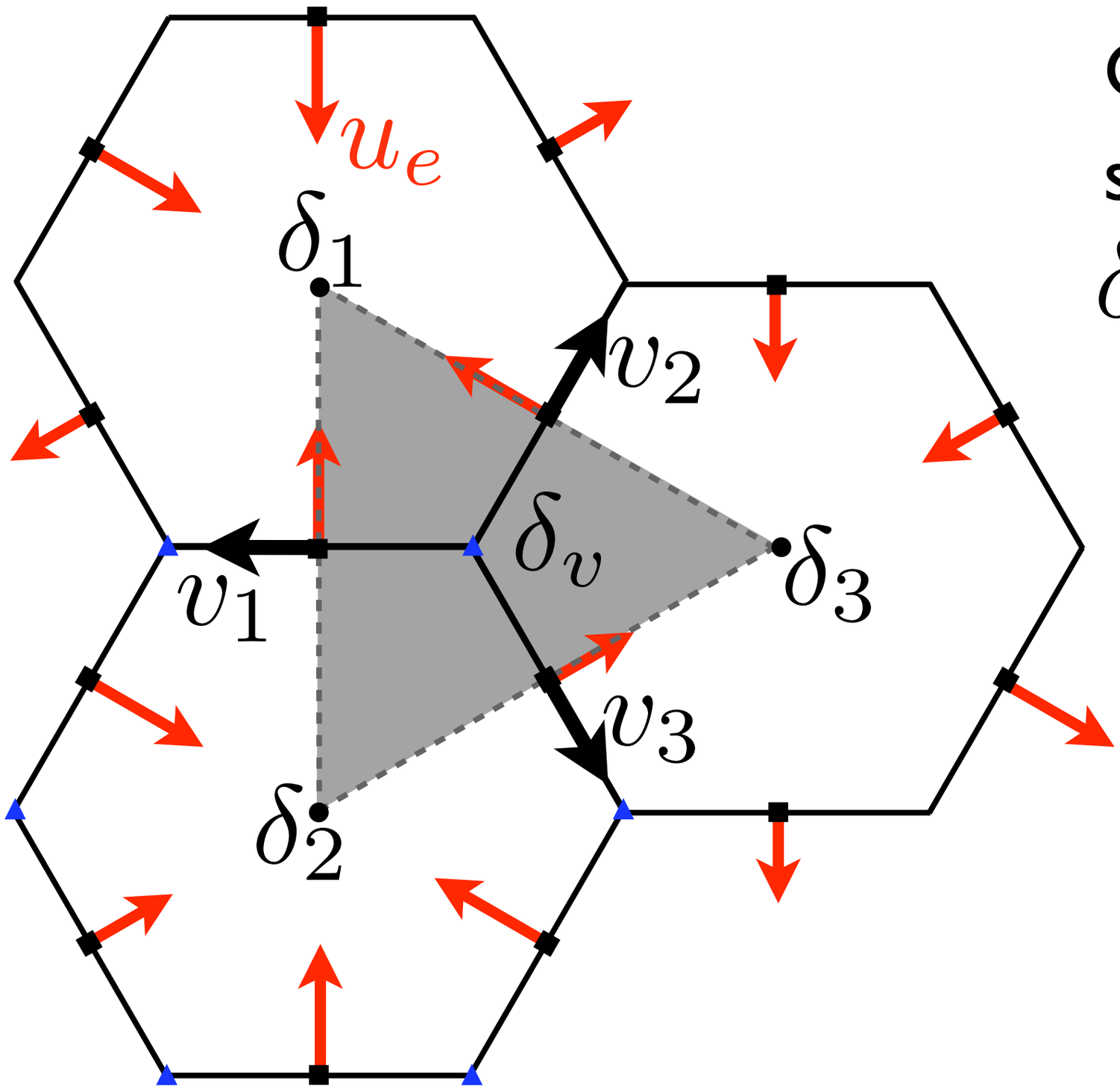


As with all C-grid methods, the biggest challenge is how to reconstruct the nonlinear Coriolis force. In this system, ALL vorticity dynamics are contained in this terms.

1) How to compute $[hu]_e^{\perp}$?

2) How to compute $\widehat{q}$?

The key to developing our robust multi-resolution method was solving this math problem .....



Given u_e, find $v_{1,2,3}$ such that

$$\delta_v = I(\delta_1, \delta_2, \delta_3)$$

where

I is a convex interpolant

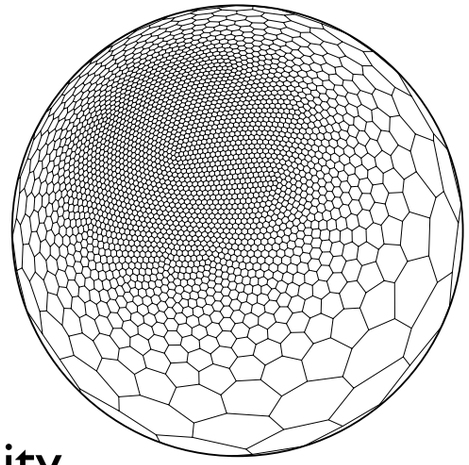
$$\delta_v = \tilde{\nabla}_d(v_{1,2,3})$$

$$\delta_i = \tilde{\nabla}_p(u_e)$$

$\tilde{\nabla}_d$ discrete div on dual

$\tilde{\nabla}_p$ discrete div on prime

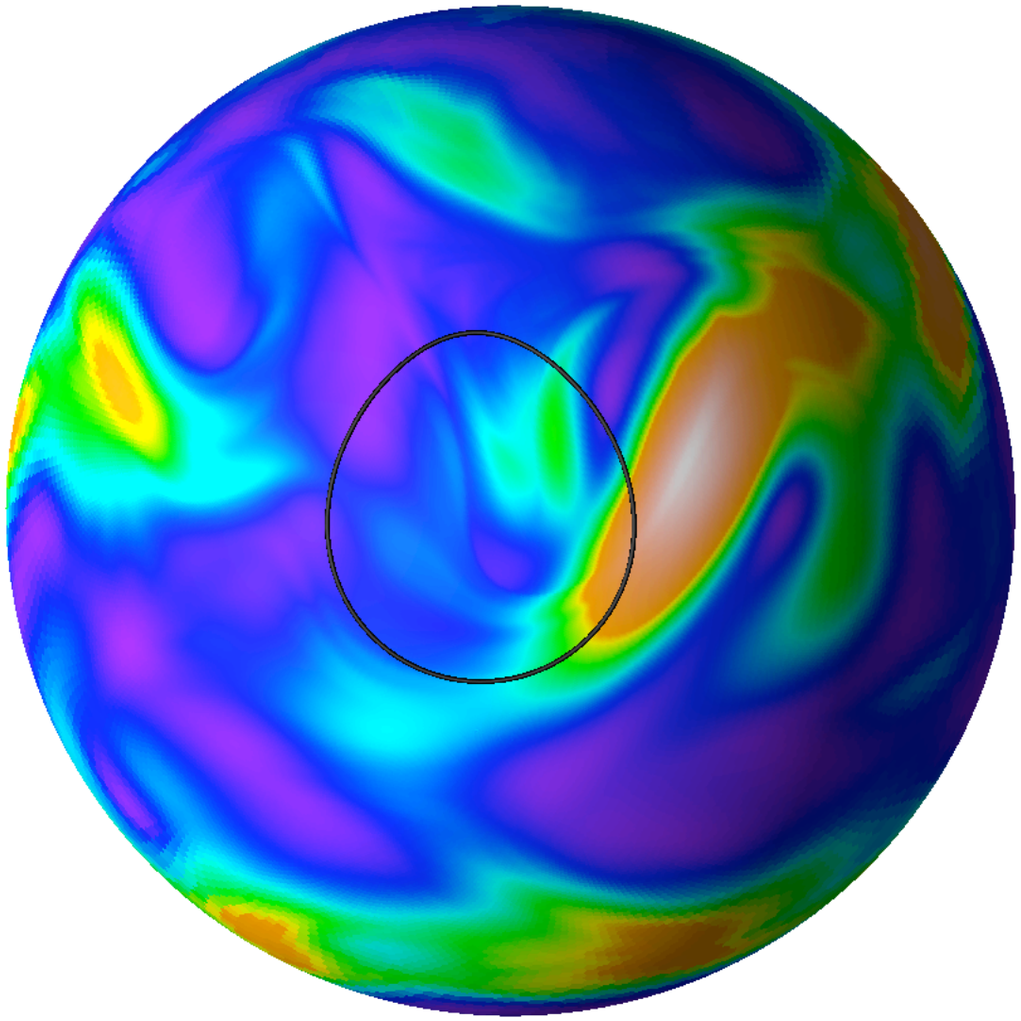
Variable resolution in the shallow-water system



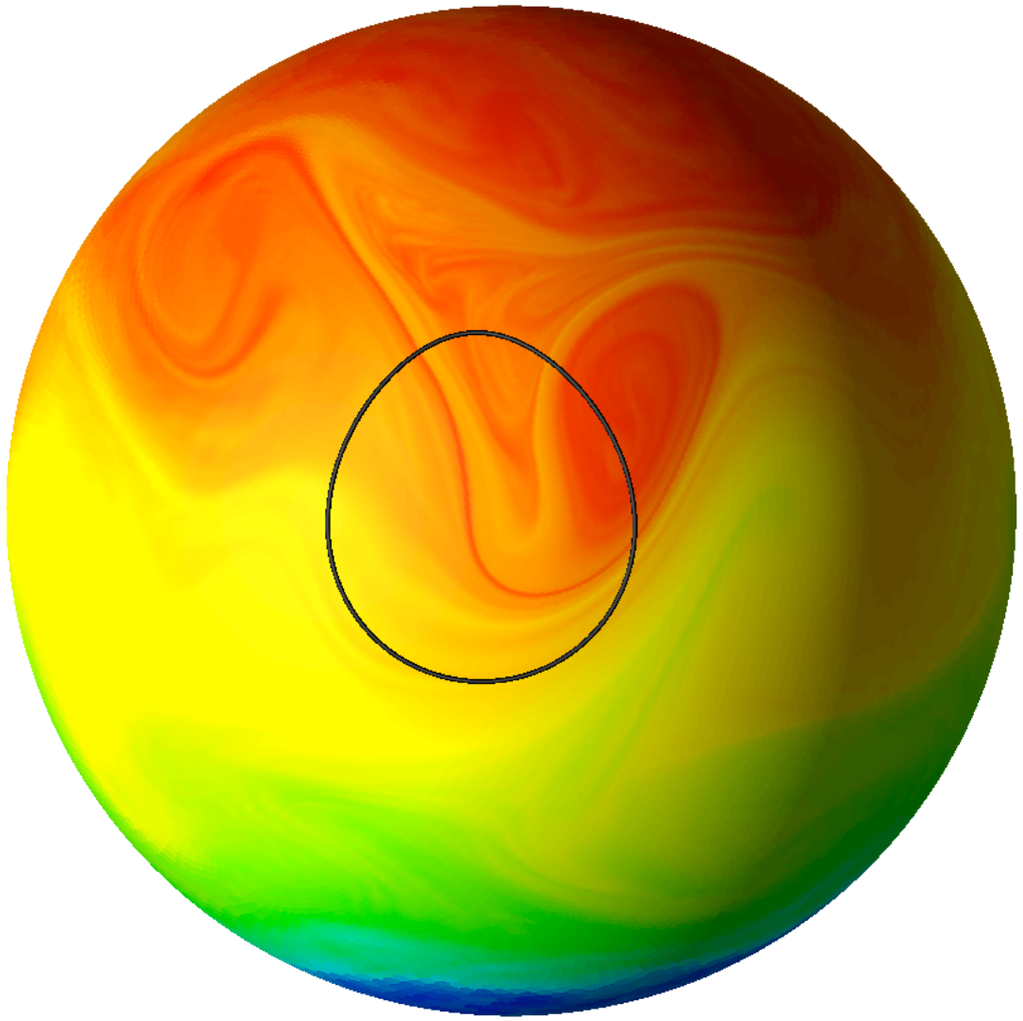
x16, 163842 nodes, shallow-water test case #5, day 50

(20 km / 320 km resolution)

kinetic energy

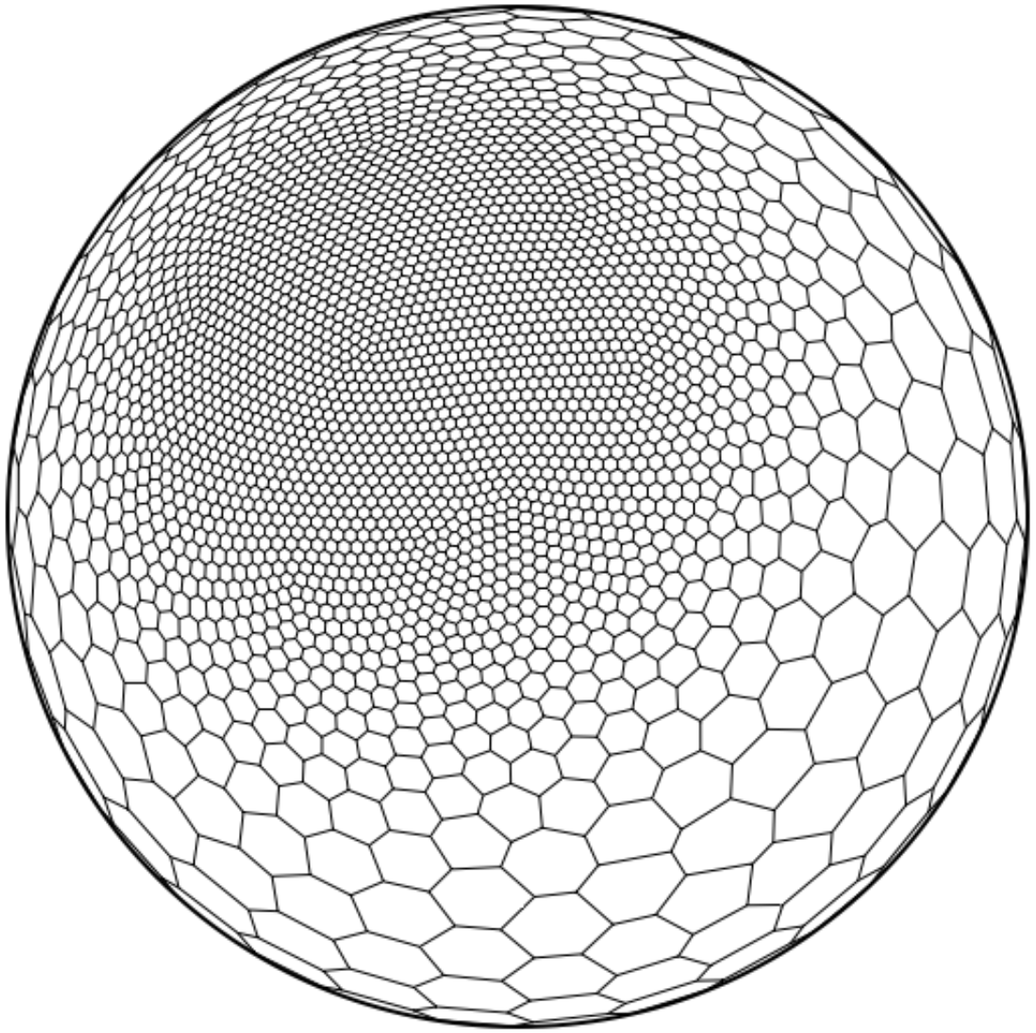


potential vorticity

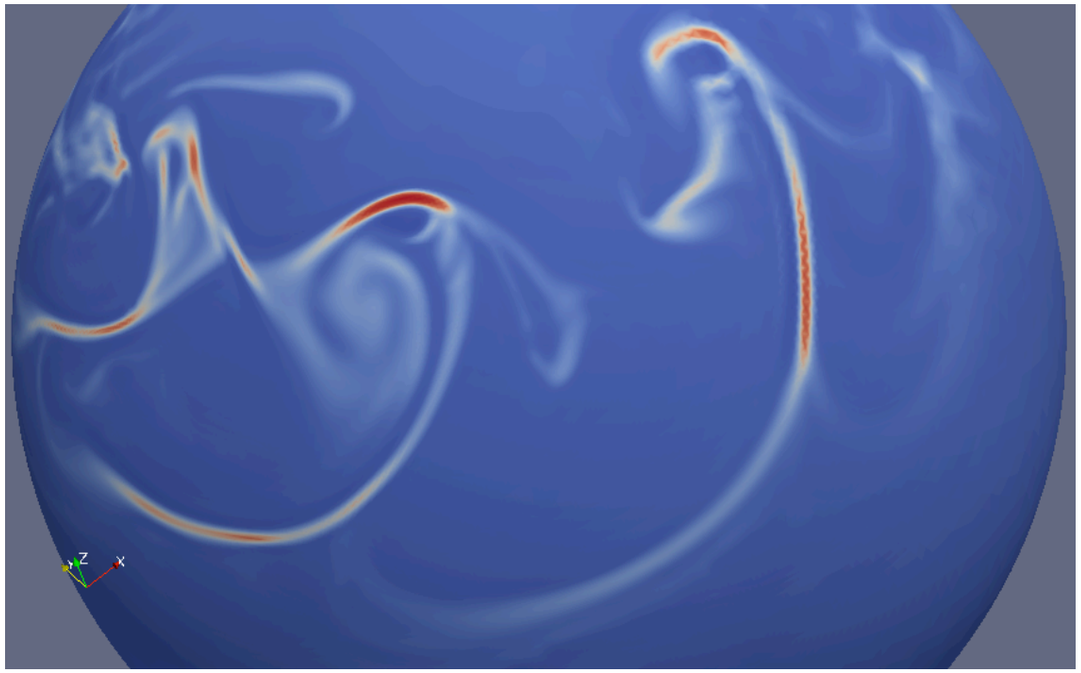


The numerical solution conserves mass and potential vorticity to round-off error. Total energy is conserved to within time-truncation error. Potential enstrophy is dissipated with a user-defined, mesh-invariant time scale.

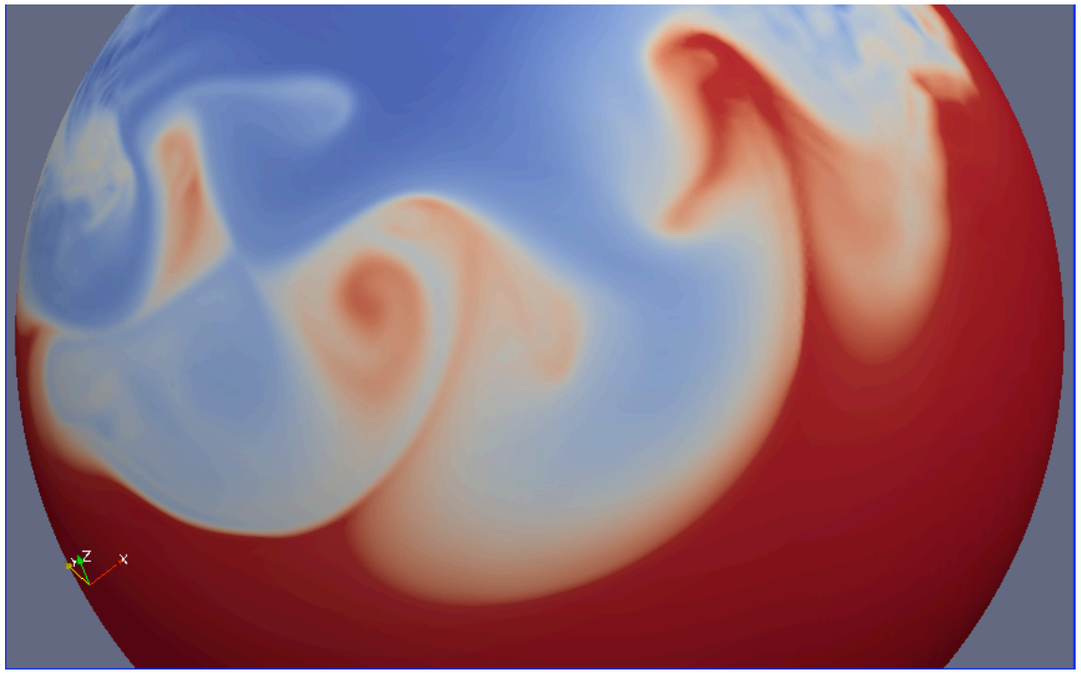
Solving the primitive equations: a global hydrostatic atmosphere simulation.



This is the Jablonowski and Williams baroclinic eddy test case on a mesh with 40 km grid spacing in high resolution zone and 320 km grid spacing in low resolution zone.



relative vorticity



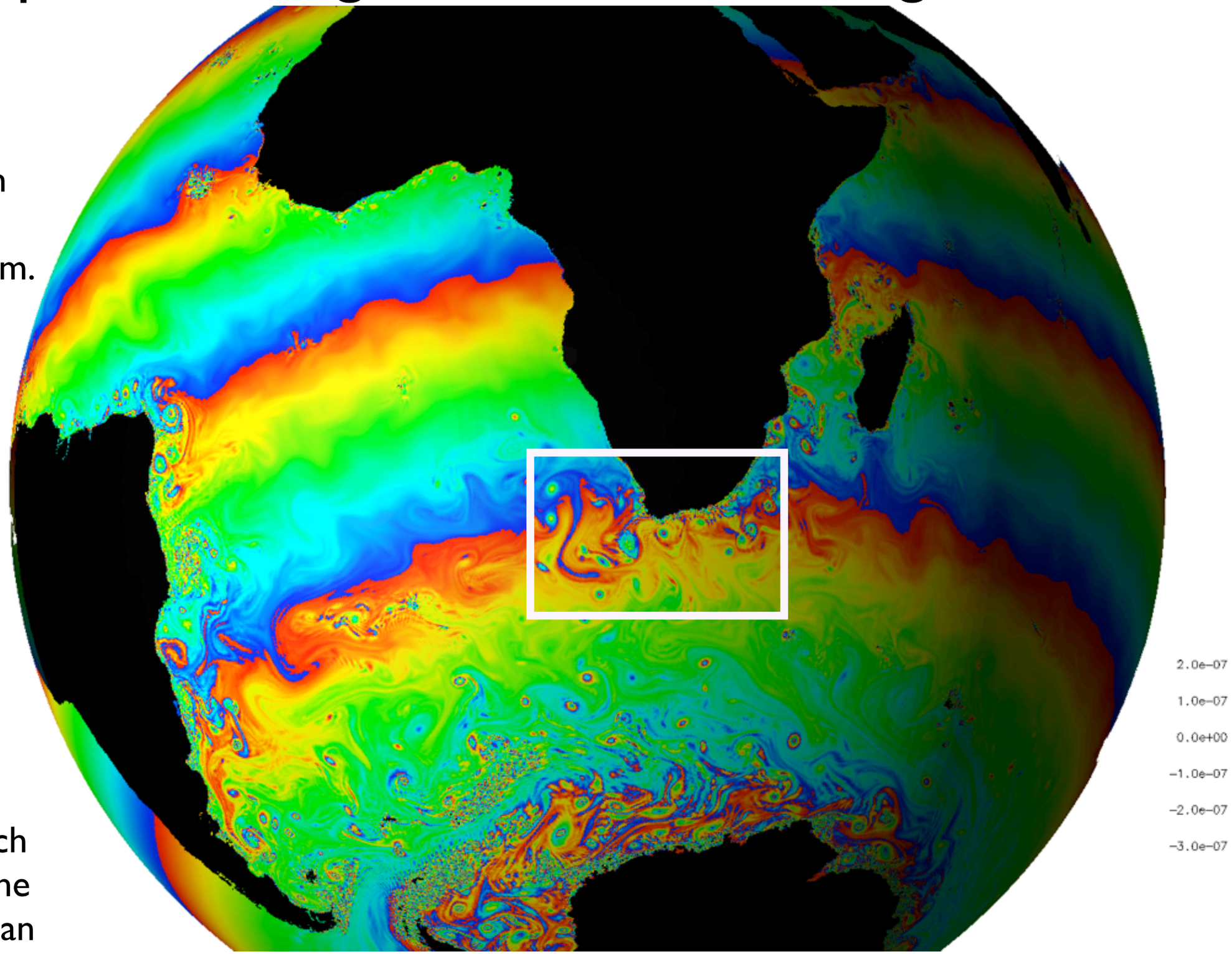
potential temperature

An application to global ocean modeling ....

Uniform and variable resolution Voronoi tessellations have been created at resolutions between 120 and 15 km.

Right: Global 15km mesh, PV shown, single-layer, flat bottom.

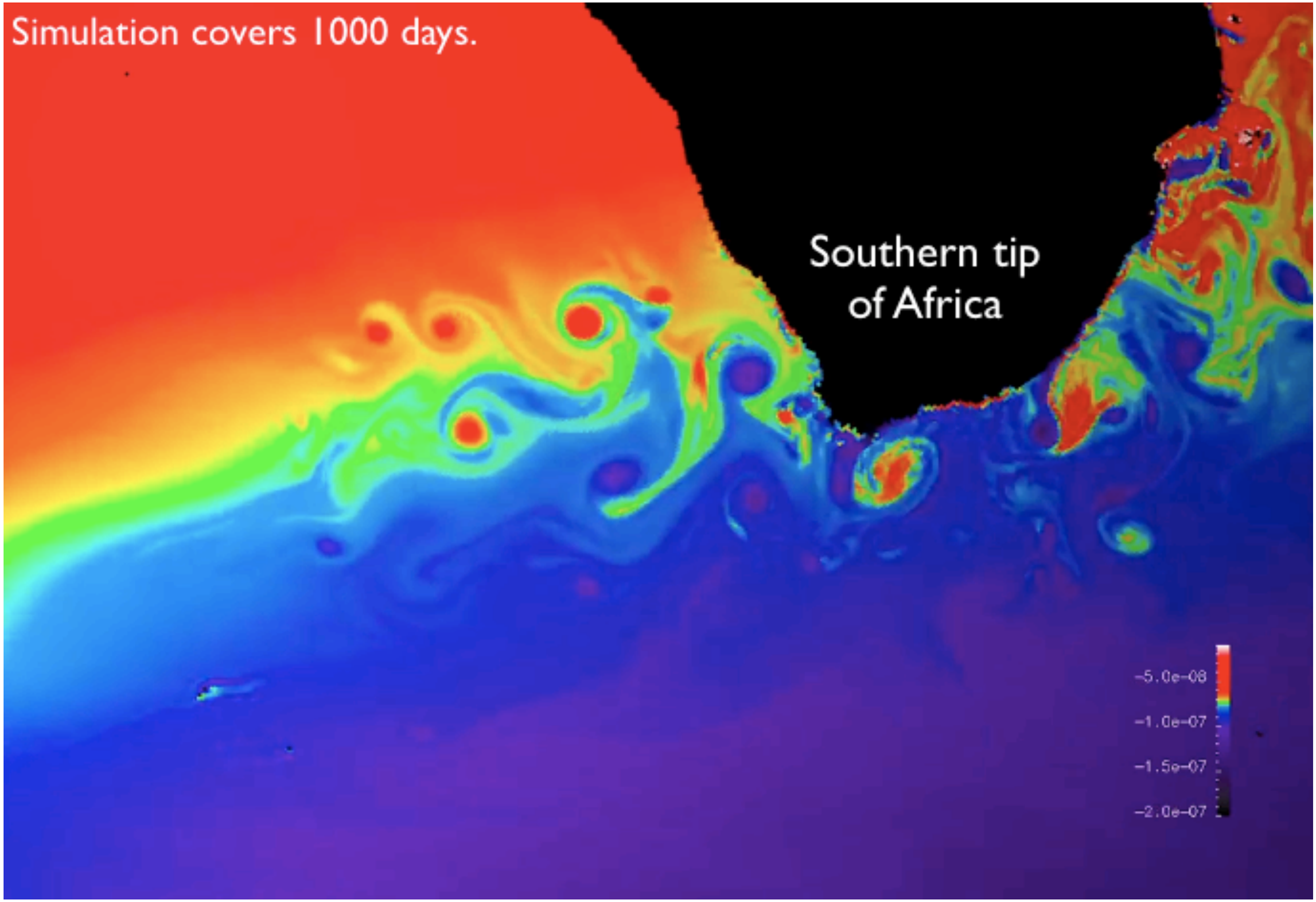
The meshes use nearest-neighbor search from ETOPO2 to define land/sea mask and ocean depth.



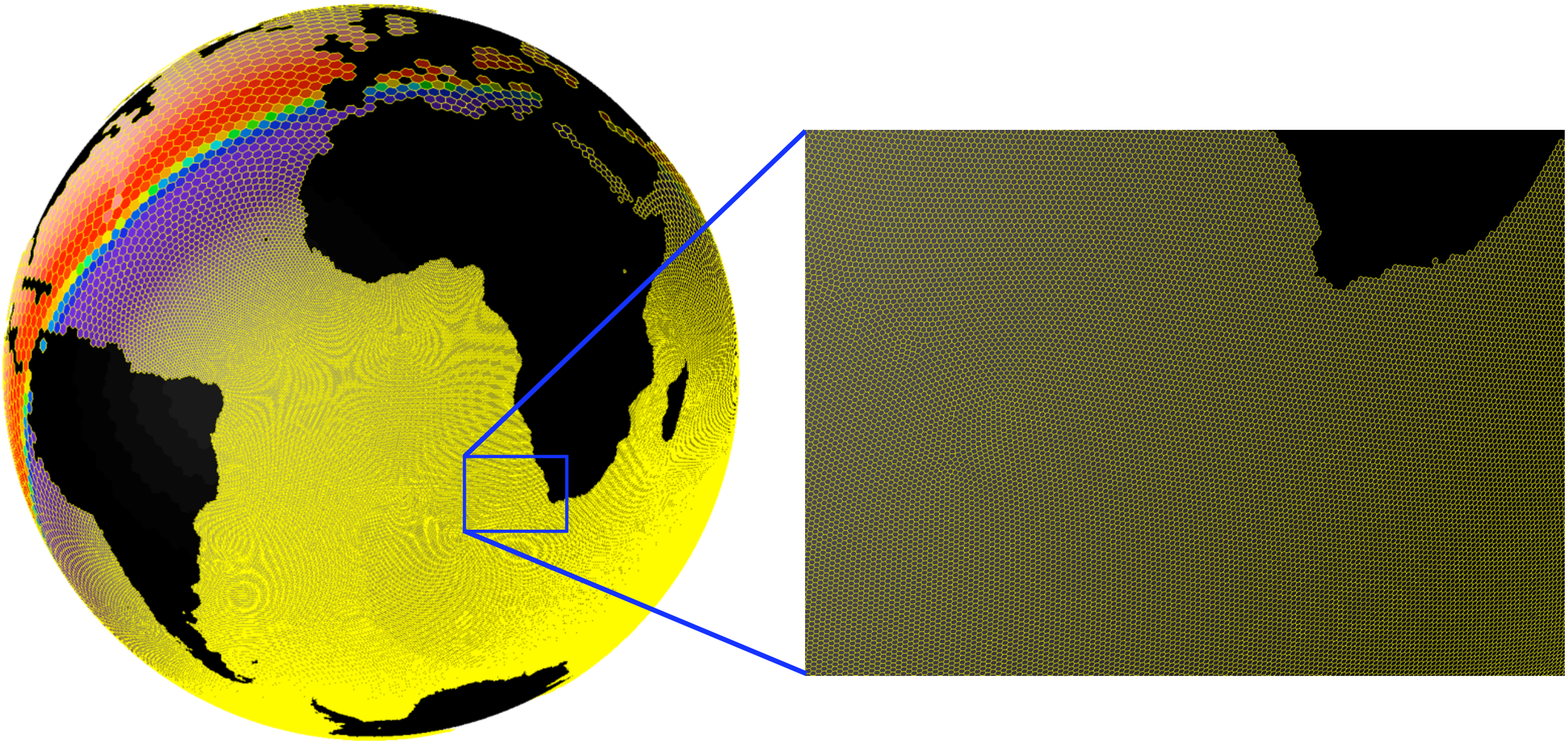
Total potential vorticity is shown.
Color scale chosen to highlight gradients in PV.

MPAS Ocean Model:

Global eddy-resolving simulation showing total potential vorticity.

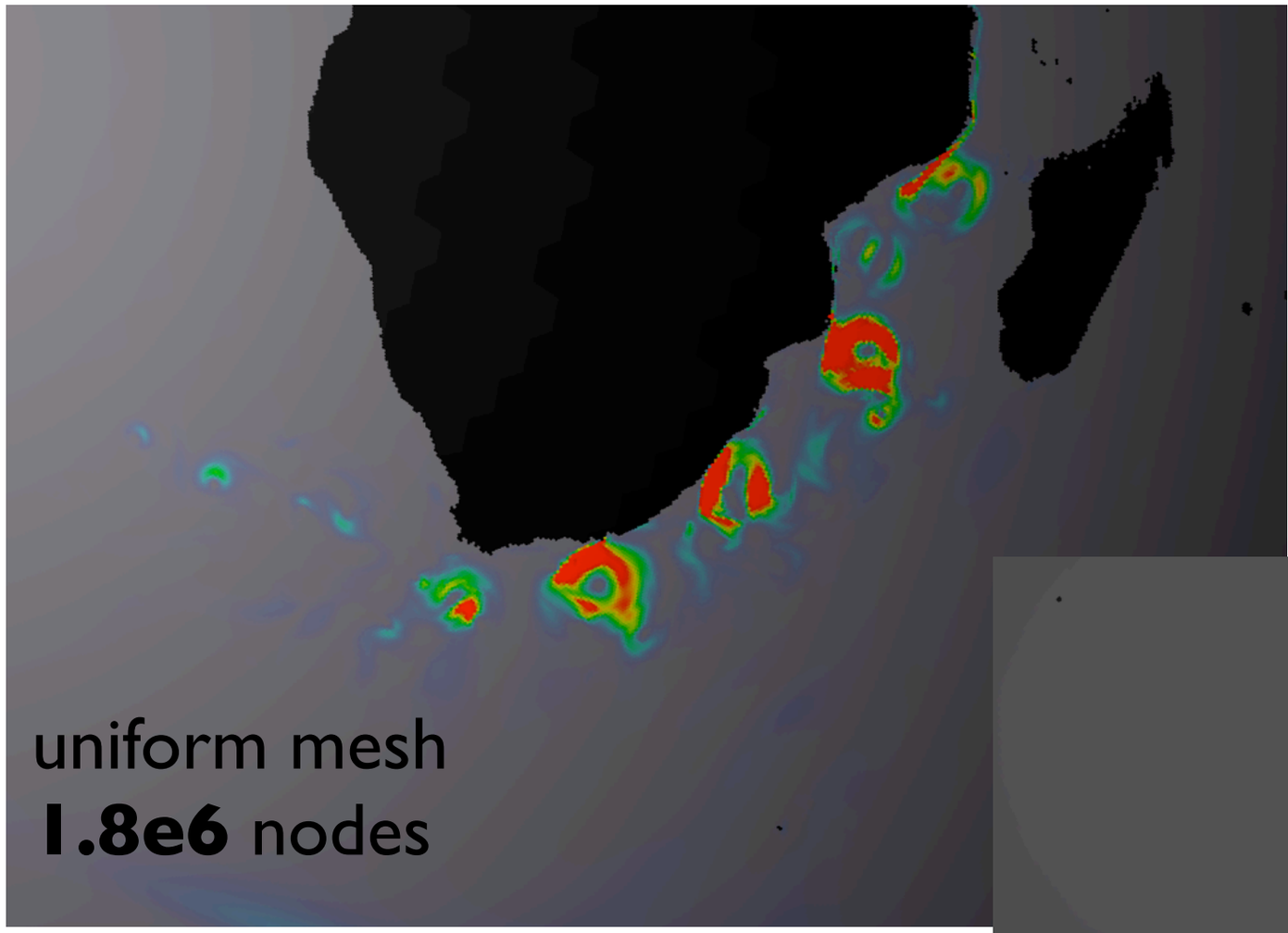


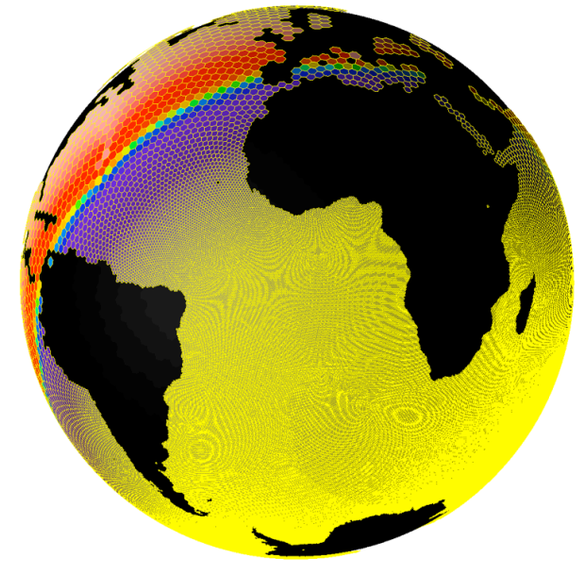
Ocean modeling with variable resolution meshes ....

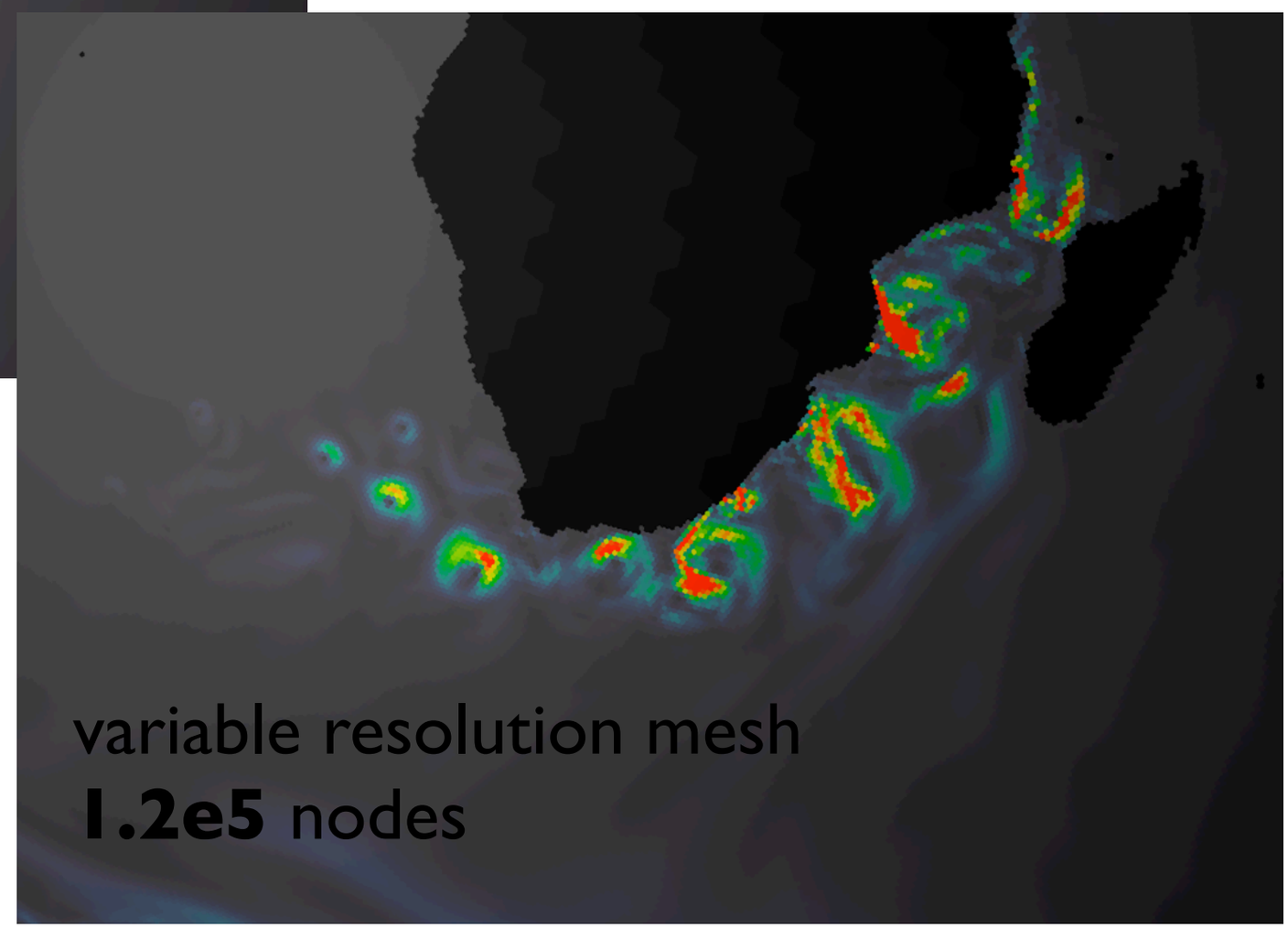


Mesh grid spacing varies by a factor of 8, ranging from 25 km to 200 km. This mesh has about 1/10 the number of nodes as the globally uniform 15 km mesh.

Comparison of quasi-uniform to variable-resolution simulation.



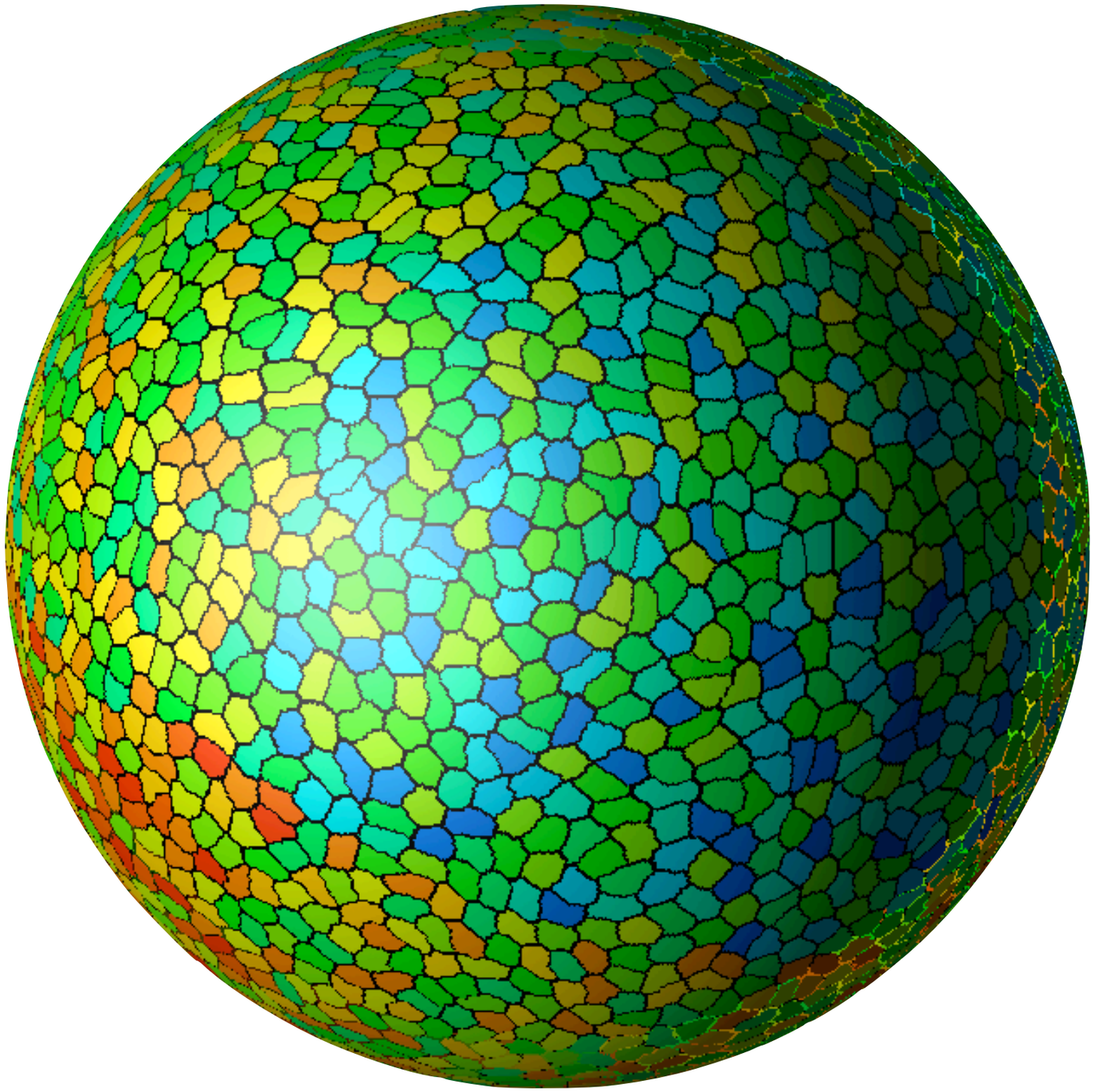




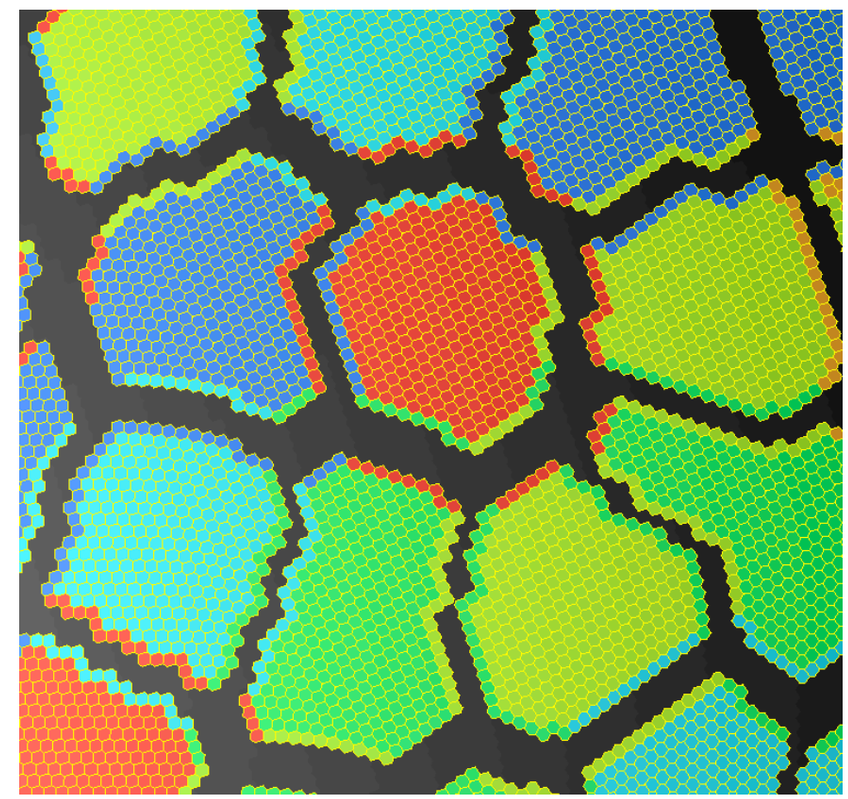
Both figures show kinetic energy at day 1000 of simulation with same color scale.

Both simulations are conducted with the same executable with the same parameter settings.

Domain decomposition is done using ParMetis.



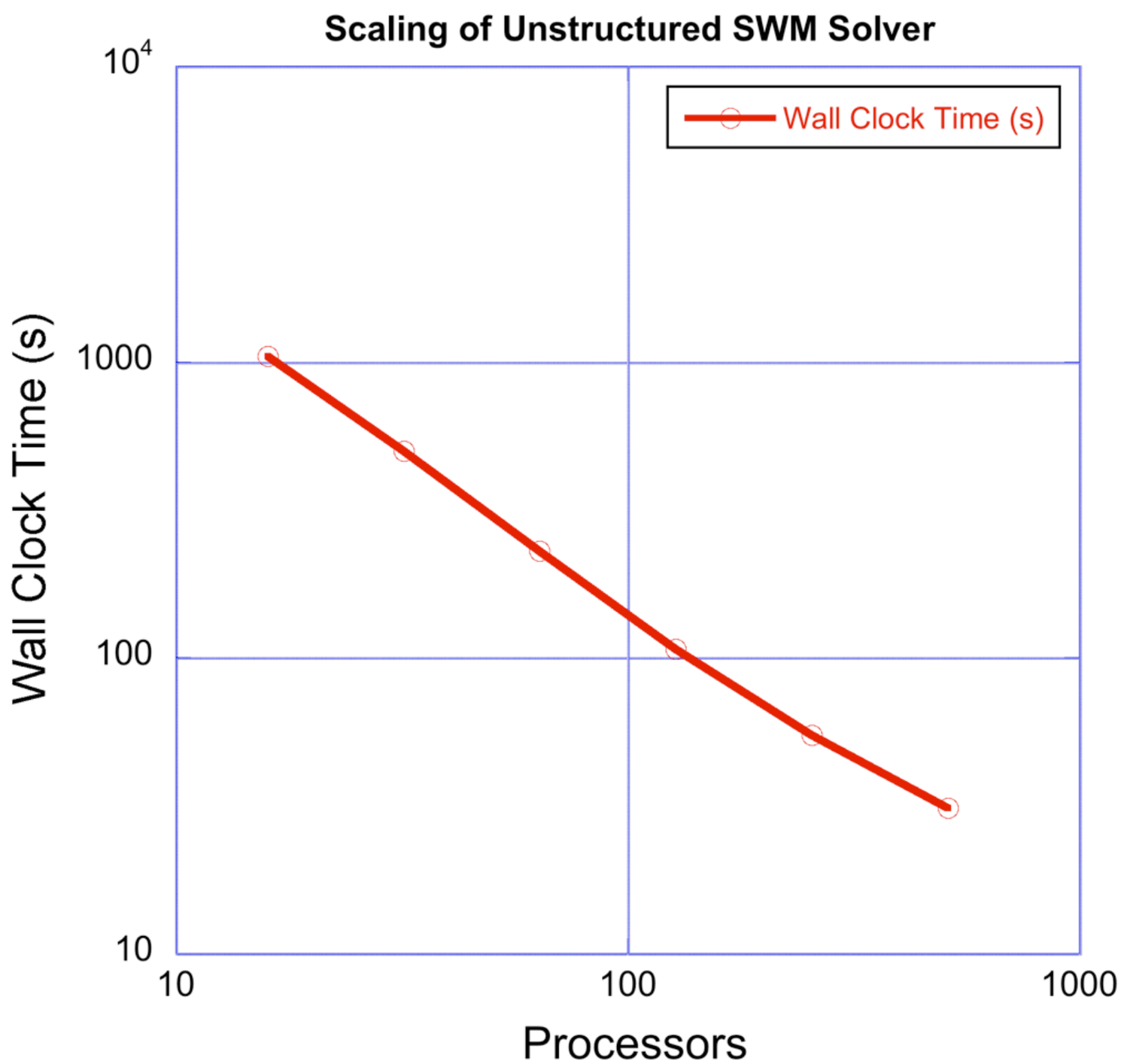
Each block is
assigned to a node.



Each block includes
a halo region of
arbitrary width.

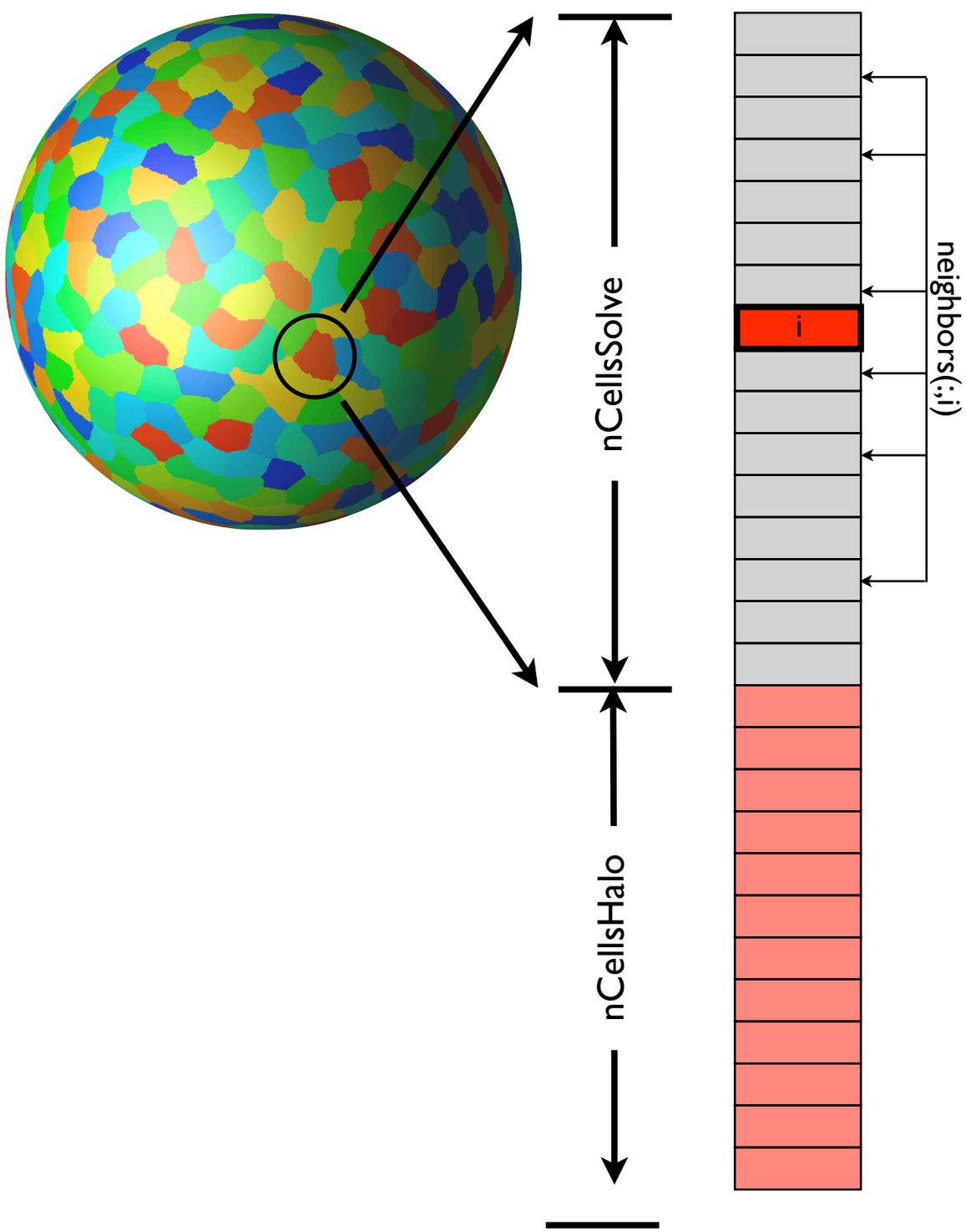
An early look at the strong scaling of the prototype system.

An analysis of the domain decomposition strategy in comparison to its peers (LANL POP and SNL HOMME) indicates that we should expect strong scaling out to O(100K) nodes with a global mesh resolution of approximately 10 km.



Lobo: AMD Opteron cores for computation, using an Infiniband interconnect. 272x16-core nodes for production capacity computing. Each node has 32 GB of non-uniform-access memory. CPUs run at 2.2 Ghz and have 0.5-MB L2.

Challenge #1: Computational Efficiency



All neighbor data required to compute spatial derivatives and averages is done via indirect addressing using, for example, neighbors(:,i).

We attempt to mitigate these non-uniform data access patterns in two ways:

1. The ordering of the cells is determined, for example, by Reverse Cuthill-McKee (RCM) to maximize cache reuse.

2. The data access pattern is repeated in the vertical, leading to arrays dimensioned as mass(nVertLevels, nCellsTotal, nBlocks).

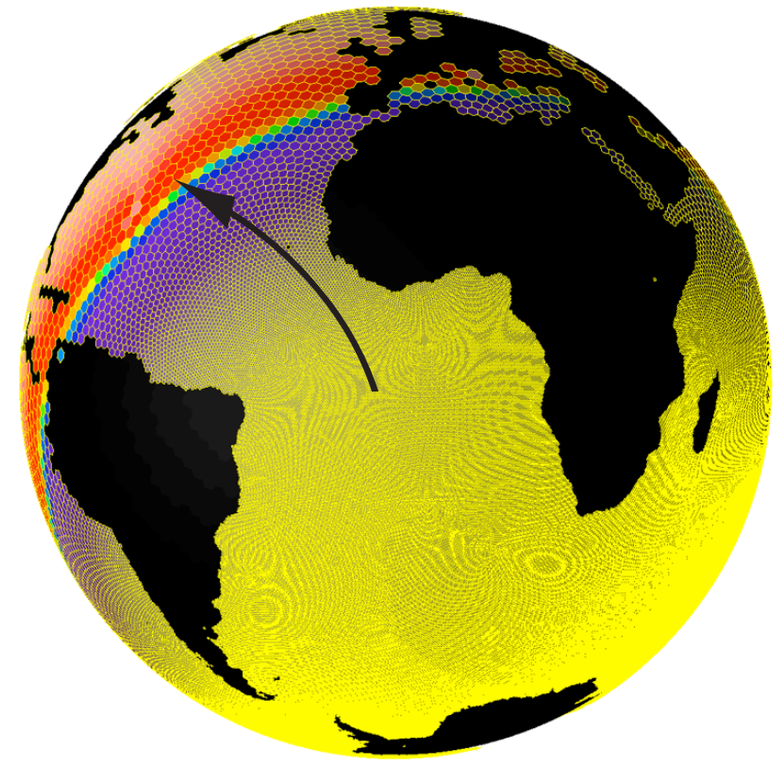
Still, we have a significant challenges in competing with models based on uniform data access patterns and will have to reconsider all aspects of our algorithms.

Challenge #2: Scale-Aware Parameterizations

We have generated a modeling approach that allows eddies to be resolved regionally.

By construction we have designed a system where important phenomena are resolved in some locations but not in others.

As a result, we obligated to develop scale-aware parameterizations that can seamlessly "turn-off" as the underlying phenomenon become resolved.



ocean sub-mesoscale eddies **resolved**

ocean sub-mesoscale eddies marginally resolved

ocean sub-mesoscale eddies **parameterized**

ocean mesoscale eddies fully **resolved**

ocean mesoscale eddies resolved

ocean mesoscale eddies **parameterized**

0.1 km → 1 km → 10 km → 100 km

mesh resolution

An idea codified ....

Model for Prediction Across Scales:

A comprehensive multi-scale approach to climate modeling

MPAS is a joint NCAR/LANL model development effort.

NCAR is developing a global non-hydrostatic (regionally cloud resolving) atmosphere model.

LANL is developing a global hydrostatic (regionally eddy resolving) ocean model

LANL is developing a (regionally ice-stream resolving) ice sheet model.

All MPAS models are build for a common software framework that handles memory allocation, domain decomposition, I/O.

MPAS is a new approach to climate system modeling.

At a minimum it will be disruptive. At a maximum it will be transformative.

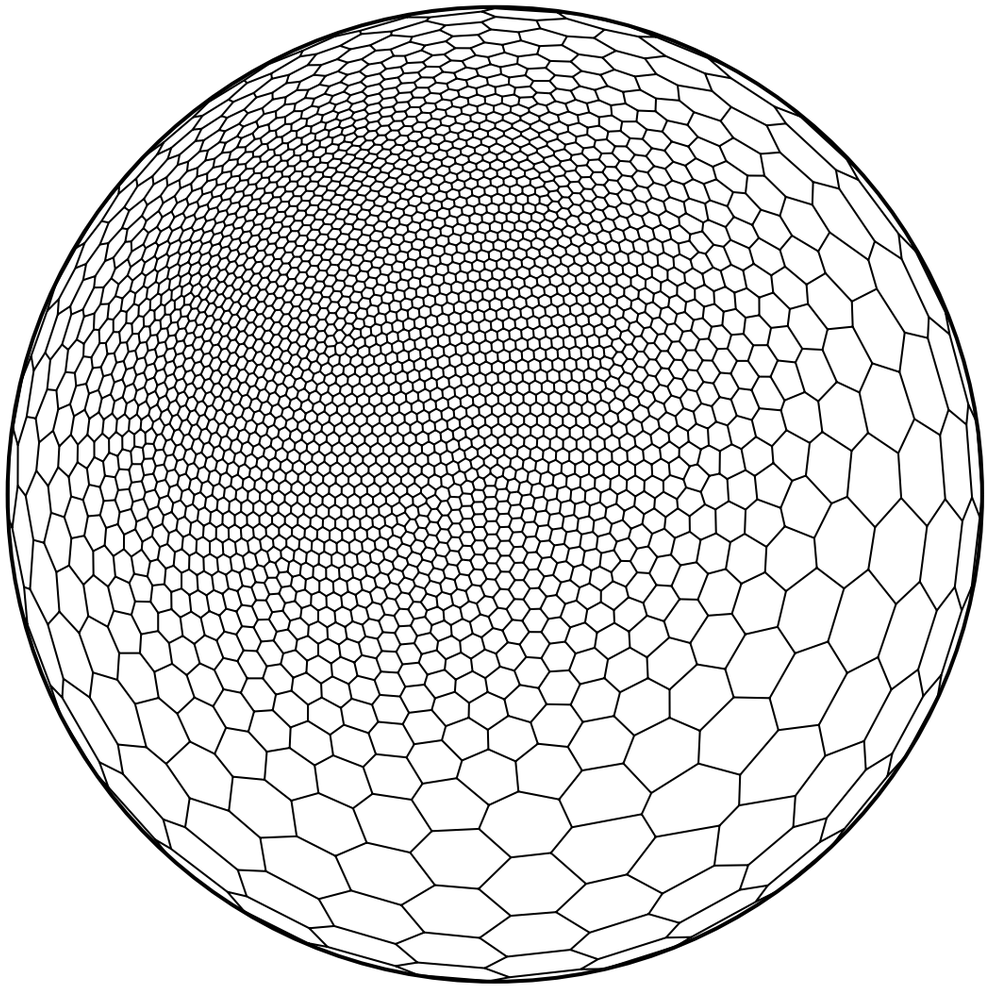
Looking forward:

A comprehensive multi-scale capability will be characterized by three attributes:

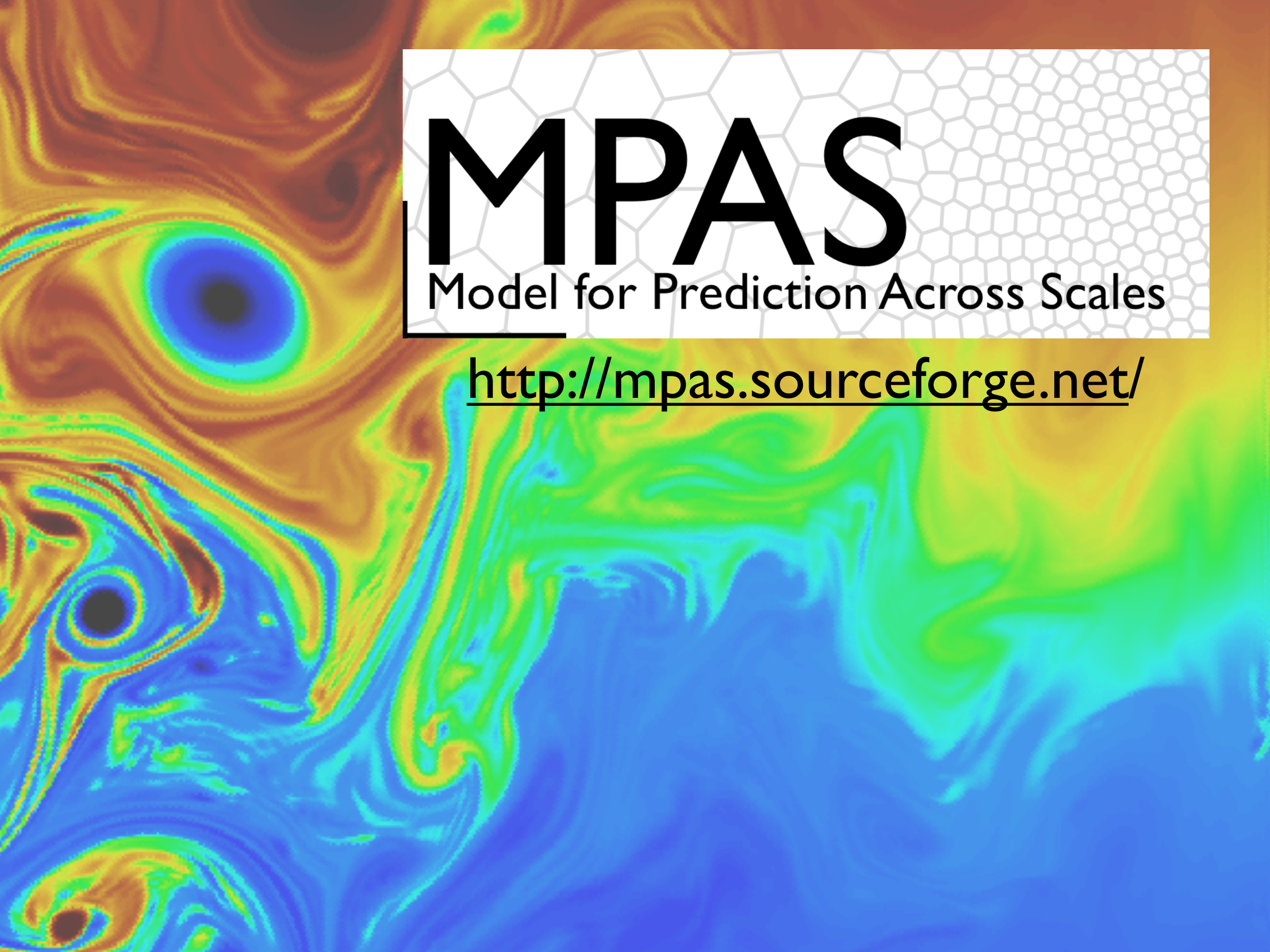
1. **Multi-resolution**: The ability to resolve different spatial and temporal scales in different parts of the global domain.

2. **Scale-aware closures**: The ability to transition seamlessly from modeling a process directly through simulation to modeling a process indirectly through parameterization.

3. **Multiple governing equation sets**: The ability to use the appropriate (and different) equation sets in different parts of the global domain.



MPAS

Model for Prediction Across Scales

http://mpas.sourceforge.net/